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AEROSPACE CREW EQUIPMENT LABORATORY

WEPTASK RAE 13C 005/2001/R005 01 01
PROBLEM ASSIGNMENT NO. 005-AE13-16

Determination of Human Tolerance
to Negative Impact Acceleration

NAEC-ACEL-510 28 Nov 1963

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ADMINISTRATIVE INFORMATION

Defense Purchase Request T-9645 (G) was assigned to the Aerospace Crew Equipment Laboratory on 22 August 1962, by the National Aeronautics and Space Administration (Manned Spacecraft Center) outlining a study to be conducted to extend the measured exposure of human subjects to negative (tailward, eyeballs up) impact acceleration. NAVAIRENGCEN letter XG-4:EH:alc 7307 (4040) of 16 August 1962 requested a Problem Assignment to cover this work. Accordingly, 005-AE13-16 was assigned on 26 September 1962, under WEPTASK No. RAE 13C 005/2001/R005 01 01. BuPers letter PERS-A212-kn of 13 Sep 1962 indicated that SECNAV permission for human subject participation in this study was granted on 7 September 1962.

The Aerospace Crew Equipment Laboratory extends its appreciation to the following subjects who made this study possible by their participation.

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ABSTRACT

Presented in this report are the results of a program conducted to extend man's knowledge of short term negative acceleration as it effects humans. Subjects, fully restrained, have been exposed to increasing increments of velocity change under controlled conditions and measurements obtained of their body displacements, velocity and acceleration. The role of the restraint harness as a determinant of subjective response and tolerance to the input are also discussed.

INTRODUCTION

The present concept for recovery of Project APOLLO astronauts includes parachute descent of the command module following re-entry into the earth's atmosphere, with terminal ground impact. Because of the possibility of swinging oscillations of the command module, and/or cross-winds close to the earth's surface, adequate protection must be provided to the astronauts from impact forces directed along any of a great number of body axes. For reasons of economy, as well as those relating to space and weight limitations, force-attenuating systems to be incorporated within the command module must be designed to achieve maximum effectiveness and efficiency. Meeting such requirements depends in turn upon a knowledge of the tolerance of the human body to applied accelerative impact loads. The amount of applicable knowledge which already exists is limited; it is the purpose of the studies described in this report to provide data regarding human tolerance to negative impact acceleration which are directly applicable to Project APOLLO requirements.

"Negative" acceleration refers to linear acceleration directed through the long axis of the torso, so that the viscera tend to be displaced headward with respect to the skeleton. Additional terms currently in use include: "eye-balls up", "head-to-seat", "footward", and "tailward" acceleration. The most recent designation for this acceleration is $-G_z$, which, like the other terms mentioned, refers to a pilot sitting upright in an aircraft. The most common aircraft maneuver producing a negative acceleration is the push-over, or outside loop. This kind of maneuver causes visceral and body fluid shift toward the head; resulting experiences of head fullness and "red-out" are quite disagreeable and may have relatively long lasting aftereffects. Depending upon exposure duration and magnitude of acceleration, cardiac slowing, reduction of respiratory ventilation and subcutaneous and submucosal hemorrhages of the head have been observed in pilots exposed to negative acceleration.

When the duration of applied acceleration is less than 2 sec., it has been referred to as "abrupt" (1). We have used the term "impact" to designate brief pulses of acceleration lasting only fractions of a second, since they are most usually encountered in crash situations. Experience with negative impact acceleration effects is extremely limited. Experimental data most pertinent are largely derived from downward ejection seat system studies. In such cases, the applied accelerative force is added to that already acting on the seat-restraint-man system due to the earth's gravity. In the situation discussed in this report, supine orientation of the body results in the accelerative force due to gravity acting almost perpendicularly to the force from the applied acceleration. In addition, the restraint and support system used in the present study is unique, and its effect upon system response can be expected to be quite unlike that of a more conventional shoulder strap-lap belt configuration. Initial orientation and relative positions of body parts and restraint components depend to an important degree upon attitude of the accelerated mass in the earth's gravitational field. The findings of this study are therefore only

directly applicable to the conditions investigated, and previous experience under other conditions can only serve as a limited guide.

Unfortunately, the word "tolerance" has no exact meaning, when used in the present context. It is not meant to imply a maximum limit which cannot be exceeded without producing serious injury or death. If a scale of severity could be established, tolerance in the present instance would mean a level between moderate subject discomfort and minimum reversible tissue damage. Presumably, subjects experiencing the maximum negative accelerations employed could still take effective action almost immediately involving coordinated mental and motor functioning. However, in view of almost total ignorance regarding the dynamic behavior of bodily organs and parts under impact loading, it would be extremely risky to exceed the limits described in this report, without exercising very great caution.

WORK STATEMENT

The ACEL, at the invitation of the National Aeronautics and Space Administration, Manned Spacecraft Center, has participated in a program to expand the measured experience of human subject exposed to lateral and tailward acceleration. This program had a twofold purpose: namely, to help fill the human experimentation void in the impact region and secondly, to supply NASA with the type of input information necessary for designing an optimum protective environment for the crewman to increase his survival chances during a maximum impact load exposure.

Specifically, the area of investigation undertaken by the Aerospace Crew Equipment Laboratory, (ACEL), was to expose human subjects to tailward impact loads, beginning at a load level known to be tolerable and physiologically safe, then proceeding progressively to more severe acceleration and impact velocity experiences. The program would be terminated when specified design limits were reached, or a G level beyond which subject safety might be compromised.

The statement of work as detailed in the NASA Defense Purchase Request T-9645(G) follows:

1. Objective. Extend the measured exposure of human subject receiving tailward acting impact loads to 15G and if possible, 20G.

2. Approach. Human subjects are to be exposed to tailward acting impact loads of 10G, 250-500G/sec rate of onset, and a 10 ft/sec velocity change, using the HG-1 Linear Accelerator located at ACEL. The rate of onset should be raised on successive firings (within equipment limitations) to approximately 1000 and 2500 G/sec, and the velocity change raised to 15 and 20 ft/sec for each new rate of onset. When the 10G level is verified, the plateau level will be raised to 15G, and rate of onset and velocity changes raised from 250 G/sec and 10 ft/sec as above. Upon completion of the 15G level, the 20G level will be investigated. Control of the velocity change is more important than rate of onset.

3. Support and Restraint. The restraint and support system which will be used shall consist of the following:

a. A vest type chest restraint integrated with shoulder straps.

b. An integrated lap belt and Y straps.

c. Wide thigh straps.

d. A recessed couch using the micro balloon principle for universal fit: leg-thigh and thigh-torso angles will be 110 degrees: back angle will be 5 degrees.

e. A mock-up, drawings, and photographs of restraint system to be used will be furnished by NASA. Contractor will be responsible for fabrication and proof testing of actual restraint and support system to be used.

f. A Mercury helmet with interchangeable lining will be furnished by NASA.

4. Instrumentation and Data Reduction

a. The acceleration of the couch or couch support structure will be measured in the 3 major axes at a position as near the center of the torso as possible. The accelerometers are to be mounted on structures rigid enough to prevent low frequency (under 150 cps) shuddering.

b. One copy of reduced data, to include the acceleration time history from each firing, will be furnished with the final report.

PROCEDURE

Accelerator

The HG-1 Linear Accelerator referred to in the work statement, is a hydropneumatic sled facility, (Fig. 1 and 2). It is currently being used at the ACEL for research and development projects associated with air crew crash protection and the dynamic evaluation of emergency escape systems, associated personnel and cockpit equipment. It has been used extensively to conduct acceleration studies on human subjects and aircraft seat systems under forces simulating impact conditions, to provide maximum subject restraint and hardware reliability.

The catapult is capable of producing sustained accelerations from 2G to 45G over displacement strokes varying from 6 in. to 9 ft. An end velocity of 150 ft/sec may be attained for the maximum stroke and acceleration condition. One of the interesting features regarding the catapult rate of acceleration buildup is that it approximates a square wave for accelerations above 5G but can be varied within limits to give a ramp onset of reduced slope for any G level.

The catapult obtains its accelerating energy from the expansion of a fixed air mass exerting pressure on the back end of a piston plunger. The plunger freely coupled to the end of the sled is initially retracted into the engine. Upon actuation the air pressure forces the plunger forward transmitting the accelerating force directly to the sled bearing against it. The sled moves freely on machined tracks which extend 386 ft. In its present design configuration, the vehicle will accommodate test pay loads weighing up to 1500 lbs. within the dimensions of 9 ft. long, 7 ft. high and 6 ft. wide.

Couch and Restraint Design

ACEL designed and fabricated a simulated space couch and harness restraint system based on requirements outlined by NASA for the APOLLO impact program. The design approach was for an operationally usable system which would be contoured and adjustable to accommodate the various subjects, but would not impede the inertial motion of the subject except for the restraining action of various tie-down straps.

Figure 3 provides an overall pictorial view of the final design configuration of the space couch.

The basic box-like metal foundation of the supporting couch was fabricated from .0 62 SO aluminum, heat treated for additional strength, and measures 6 ft. long x 3 ft. wide x .47 ft. high. It was designed so that the shoulder, chest and lower body retention harnesses terminate into ad-

justable fittings built into the structure to accommodate precentile dimension variations. A large pedestal was attached at the foot of this structure for proper positioning and support of the subject's thighs, legs and feet. Adjustable cupped retention closures mounted to the pedestal, aided in restraining the subject's limbs. A subject seated in the couch would assume both a back-to-thigh and thigh-to-lower leg angle of 107 degrees. Right and left adjustable lateral torso and arms support assemblies were attached to the face of the base structure. A one inch thick ensolite pad lined all bearing surfaces on the couch, providing the subject with proper body contour and insured comfort without impeding subject translation, (Figs. 3 and 4). The couch assembly, supported on four mounting trunnions, was fastened to the sled at an angle of 5 degrees from the horizontal, with the head up.

The restraint system (Fig. 5), was designed and constructed by the ACEL, patterned after a prototype model supplied by NASA. Some changes and modifications were adopted in the selection of materials and fabrication to allow for more positive restraint and ease of adjustment.

Basically the restraint system consisted of the following:

a. Adjustable right and left shoulder straps.

b. Cross chest strap.

c. Integrated lap belt and upper thigh retention assembly.

d. Special thigh retention harness.

e. Foot anchor straps.

f. Lap belt tie-down V strap.

The restraint system was constructed of dacron webbing combining 1-3/4" and 3" wide straps for shoulder, chest and lower torso retention. Two universal type corsets, constructed of nylon material with zippers for easy donning, restrained the subject's thighs. Lacing was provided on each flap of the corset to draw the material tightly aroung the thigh. The original integrated pelvis and thigh retention harness consisted of a 3" MIL-W-25361 type IV web sewn into the shape shown in Figure 6, Phase No. 1. Strap tightening and adjustment both lateral and longitudinal was accomplished by reeving the ends through standard Navy aircraft adjustment buckles affixed to port and starboard couch tie-down points. Each strap was tightened individually by relying on subject comment to balance the system. One arm of the connecting Y's which are formed by the lower restraint assembly was attached to the couch after passing over the hip. The other arm of the Y crossed over the upper thigh and tied into the couch. The intersection of the split harness was located over the subject's iliac crest. A nylon V

strap approximately 8" long, anchored the torso harness to the thigh support pedestal. The open ends of the V strap were sewn into the center portion of the lap belt and terminated with buckles. Straps attached to these buckles passed over the shoulder and fastened into the couch. Longitudinal adjustment at this attachment point allowed the straps to cross over the shoulders at various angles. The straps were fabricated with 3" wide webbing and tapered down into 1-3/4" dacron web, MIL specification W-19078.

Data Acquisition Techniques

Complete motion picture coverage was obtained from each of the 61 firings conducted on the Accelerator. Two Milliken model DBM4 cameras set at 400 frames per second (fps), were fastened to the sled on top of a grid board used as a backdrop. These cameras provided close-up detailed coverage of the subject and the harness restraint system during acceleration and sled run out. Another 400 fps Milliken model DBM-5 camera was mounted on a stationary platform approximately 8 ft. above the sled to record the overall reaction of the subject during the power stroke sequence. A battery of three high speed Eastman cameras (1000 fps) were located on a stationary elevated catwalk facing the starboard side of the sled, to provide both detailed and overall coverage of the subject's movements. Also, an Eastman high speed camera placed at ground level, approximately 25 feet from the starboard side of the sled, covered the entire action sequence.

Acceleration data was obtained for the series of tests with transducers using the strain gage resistance bridge principle. The important characteristics of these transducers including range, frequency response, model number, manufacturer and test location are listed in Table 1.

It is to be noted that the natural frequencies of the accelerometers as stated by the manufacturer are listed in this index. The frequency response in terms of constant amplitude remained within ± 5% over approximately 50% of the stated natural frequency. In the case of the two channels assigned to measure couch and subject acceleration exposure, the frequency response was limited by the selection of recording galvanometers which were flat up to 60 cycles per second. The reason for this choice was to eliminate any high frequency chatter introduced by structures which might mask the acceleration. However, the channel measuring sled acceleration and "rate of onset" data was recorded with a galvanometer having a flat frequency response of 1000 cycles per second, since the onset time duration was extremely short and required high response instrumentation. Sled acceleration was measured at a position close to the application of the driving force.

Couch acceleration was obtained by affixing the transducer to rigid structure so that its sensitive axis was in line with the longitudinal axis of the couch, which was mounted at a 5 degree angle to the sled platform. Since the cosine of this angle is .9962, no appreciable amplitude difference was noted in a comparison of couch and sled acceleration other than the filtering of the high frequency component and phase lag due to limited frequency response.

The subject's reaction to the acceleration forces was measured by two methods. Initially, a "mouthbit" attached to a small accelerometer was gripped between the subject's teeth and aligned in a direction corresponding to the thrust axis. This method was later superseded when the addition of the Goodrich pressure suit helmet interfered with the placement of the transducer. Instead, a head harness was designed to firmly locate and hold the accelerometer, Figs. 7 and 8.

Shoulder and thigh restraint loads were measured with four ACEL designed tensiometer links by reeving the harness straps through the links at appropriate locations. Refer to Figure 7 for the placement of the tensiometers on the shoulder harness.

Each tensiometer was initially calibrated up to a tension load of 1000 lbs. in increments of 200 lbs., using material identical to the harness straps. Calibration procedures included a check of sensitivity and linearity of each tensiometer under static conditions. In addition, a precision calibration resistor was placed across one arm of the wheatstone bridge just previous to each run, unbalancing the bridge and producing a galvanometer deflection representing the calibration of the entire circuit from transducer to galvanometer.

Maximum sled velocity was obtained by actuating a Hewlett Packard model 522B electronic timer. This instrument displayed the time lapse required for the sled to travel one half foot beyond the power stroke. The velocity in units of feet per second, was calculated from this data.

All transducer outputs were fed into a Heiland Model 1012 Visicorder Oscillograph for immediate analog display. The optical galvanometers used in this instrument were Heiland series M and are listed with their appropriate characteristics in Table 2. Selection of galvanometers was based upon the particular electrical and mechanical characteristics of the monitoring channel, taking into consideration frequency response, sensitivity and damping factor. Whenever higher frequency galvanometers were used, A KinTel Model 190B DC amplifier provided additional amplification voltage.

Two radio transmission systems monitored subject's EKG and EEG before, during and after each acceleration exposure. A disposable electrode consisting of a patch-type adhesive bandage with an electrode paste reservoir, a metallic screen and contact snap fastener was secured in place on the skin. Optimal EKG results were obtained when electrodes were located over the L&R clavicle, respectively (Fig. 9). This placement corresponded reasonably well to the standard limb lead I and is relatively free of muscle interference except during intervals of extreme exertion. An AVF wave was obtained by locating electrodes 3 cm. left of the seventh cervical and third lumbar vertebrae (Fig. 10).

The electroencephalographic potentials sensed by electrodes placed on the L&R temple, (Fig. 9) were carried by thin flexible wires into a battery operated F.M. transmitting and amplifying unit. This miniaturized

component, located on the sled, comprised the sending portion of a Telemetrics Inc., Model RKG-500 radio telemetering system. A companion desk model radio receiver, remotely located, received, demodulated and relayed the characteristic EEG wave to a Sanborn pen recorder for permanent retention.

An ACEL telemetering system was used to monitor the subject electrocardiographic variables. The ECG leads were fed directly into I.R.I.G. specifi millivolt oscillators which were frequency modulated by the potential differenc across each pair of leads. The outputs of the oscillators were mixed and amplified providing a low impedance multiplex signal for deviating an R.F. transmitter. All the electronics was housed in a compact telemetering package mounted on the sled. A ground station receiver demodulated the broadcast composite FM/FM telemetry signal producing a F.M. multiplex of the subcarriers. Two discriminators separated and demodulated this signal reproducing the original data channels. The data was then available for recording on a two channel Sanborn pen recorder. In addition, the ECG channels were combined on a Tektronic Oscilloscope to form a Lissajous figure giving a two dimansional vector cardiograph presentation which was photographed for data interpretation.

Figure 11 is a schematic of the ACEL radio electrocardiograph techniqu

In addition to the instrumentation, the subject's immediate recollecti of his experience was tape-recorded within 30 seconds after exposure.

Test Method - Phase I

Once the couch had been installed on the catapult sled, a short program was undertaken to prove its structural integrity and establish that the instrumentation would function properly under "G" force. An initial test was conducted using a 95 percentile Alderson rocket sled type anthropomorphic dummy, held in the couch with the ACEL restraint harness, and subjected to 25G acceleration. All systems functioned as designed and the human program was initiated. The subjects choosen to participate were naval personnel assigned to the ACEL and randomly selected from the laboratory group, (Fig. 12). Each had been previously used as a subject in other hazardous programs and all had been exposed to ejection seat accelerations. The physical characteristics of each of the subjects are summarized in the accompanying table based on using joint Navy and Air Force percentile tables.

Preselection studies included a physical examination, roentgenograms of vertebral column and skull, routine hemogram and urinalysis, and electroencephalography by conventional methods. Electrocardiograms were obtained with the subjects in a seated position. Findings were normal except for the followi one subject exhibited X-ray evidence of a congenital defect in neural arch of S1 and one subject had a low voltage electroencephalogram. Each man was give a physical examination immediately before the test. He was then strapped securely into the couch, usually by the same technicians in an attempt to keep the degree of harness tightness reasonably constant. The lower torso restraint and thigh harness were cinched up to a point bordering on being painful if the

subject had to remain so positioned for more than ten minutes. Shoulder straps were kept reasonably tight but not uncomfortable. In every case the man was completely immobilized before each firing.

For the first 38 tests, known as Phase I of the program, the straps crossing over the shoulders anchored into the couch below the shoulder line. At the 3G level, operations were temporarily halted in order to make several modifications to the restraint harness. A nylon V strap was sewn into the center portion of the lap belt, anchoring the torso harness to the thigh support pedestal. This prevented shifting of the lap belt to the upper abdomen and lower rib cage and helped distribute the major portion of the accelerating force to the pelvic girdle. In addition, the 1-3/4" shoulder strap was modified to include a 3" wide web crossing over the shoulders. The purpose of this change was to increase the contact area between the shoulder and the harne reducing the stress per unit area. With this new version of the original harne a sled acceleration of 10.7G and velocity change of 17 ft/sec was tolerated, (refer to Table 4).

Test Method - Phase II

The information obtained from Phase I was reported to NASA at a meeting held at the Manned Spacecraft Center, Houston, Texas on October 18, 196 After discussing the results including the probable factors that contributed to limiting the magnitude of subject exposure, it was decided that the followin changes be made before proceeding with the second phase of the program.

1. The shoulder straps, originally adjusted to wrap around the shoulders, were to cross over the shoulders and terminate perpendicularly into the couch.

2. The lower torso harness was to be modified to "grab" the occupant more efficiently around the pelvic girdle.

3. The sled rate of G onset which exceeded several thousand G/sec at the highest levels of exposure was to be reduced to less than 1500 G/s

4. The back-thigh couch angle of 107° was to be closed to 78° as a closer approach to the operational dimensions of the finalized couch.

Accordingly, positive action was taken for the inclusion of these new features into the program. The lower torso restraint was reconstructed and is shown in Figure 6. An adapter was fabricated and fitted to the leg pedestal to produce the desired angle change, Figure 13. In addition, the shoulder hold down fittings were modified to bring the shoulder straps closer to the neck. Tests #39 to 61 were conducted with the subjects wearing a Goodrich pressure suit helmet utilizing an anterior and posterior tie down strap system designed and fabricated by ACEL, Figures 8 and 14. The same volunteers participated in Phase II except for the substitution of Subject I for Subject C. A sled acceleration of 14.5G plateau and velocity change of

20.6 ft/sec was tolerated, (refer to Table 3).

Oscillograph Records

Included in the report is a set of data records of one of the five subjects who participated in both phases of the program (Figures 15 - 30). These sled acceleration patterns for each increment of G are representative of those experienced by the other subjects. For purposes of data interpretation, the parameters measured were defined as follows:

1. Rate of acceleration is taken as the best fitting straight line fared through the rising acceleration trace.

2. Reported peak acceleration and harness loads are the maximum amplitude measurements for both the subject and sled.

3. Sled plateau acceleration is the maximum acceleration sustained 10 milliseconds or longer. Each of these variables are available in Table 4.

Analysis of Data

It is evident from an examination of the oscillograph records that the restrained human becomes excited by the input pulse during a relatively short time and reaches his maximum acceleration near the end of the pulse duration. This response is directly related to the harness and man resiliency and lends itself to a simplified analysis. A sufficient number of parameters were available from the oscillograph records to obtain an approximation of the natural frequency of the restraint-man system. (2) This was done by comparing the response acceleration to the forcing function and correlating the results to the classical analysis of a simple springmass system under the influence of an impact sine pulse. The ratio of sled input duration to man-harness natural period (Ø), may be obtained from the family of curves, (3), plotting transient time displacement as a function of natural period (Figure 31). Ø can be determined once the ratio of elapsed time until peak response to sled input duration ($\mathcal{T}$) are known. Twenty records were chosen for the study based on the closest approach to the sinusoidal input. For the values of ($\mathcal{T}$) obtained for the records, Ø was selected from the best fitting curve. Values of ($\mathcal{T}$), (Ø), and (t_o) are given in Table 4. Also included in the table is the Transmission Factor (T.F.), the ratio of transmitted force to applied force. Noting from the table that a T.F. of approximately two resulted for each firing it is assumed that system damping is low and little pulse energy is absorbed by the damper. The results also show that the natural frequency of the "restraint-man" system varied from 3.9 to 4.7 cps. Since the analyzed record group comprised all of the subjects, the results reflect the mass variable. It is reiterated that "man acceleration" is the measured acceleration of the subject head. At the low G levels of Phase I this acceleration was generally in phase with the shoulder load and lagged the lower torso load by several milliseconds. As the input acceleration level increased and the double peaked pulse became exaggerated, the head acceleration no longer followed the harnes

load but either led or lagged by as much as 10 milliseconds. In Phase II the head acceleration was always in phase with the shoulder load and lagged the lower torso load by several milliseconds.

The measured acceleration was restricted to subject head movements but not to displacement of the inner organs which do not necessarily follow torso motion and are only indirectly accelerated by the harness. Coupling of an accelerometer rigidly to the human depends on locating an adequate body platform mount. The difficulty in locating such a mount is apparent since skin shear and compression effects do give extraneous acceleration results. Under these circumstances, the technique used to obtain head acceleration information was effective, giving good phase correlation with the tensiometer load data and a predicable wave shape.

As stated previously, the restraint and couch configuration were modified before the start of Phase II. A comparison was therefore made with th original setup to determine whether these changes altered the distribution of the load onto the various holddown straps. For purposes of analysis, an approximation was made for the total torso load under G by assuming a torso G of 1.5 times the sled G and a subject torso weight of .7 of total weight, 30% of the body mass was assumed to be restrained by other than torso restraints. The multiplication of these two figures gave a representation of the load which must be taken up by the harness and thigh restraint. After totaling the measured tensiometer loads in the two shoulder and thigh straps, this figure was expressed as a percentage of the computed torso load. The remaining load is accounted for by the other straps and thigh retention harness completing the restraint system. Table 5 presents the results of this analysis and compares the magnitude of the measured loads in Phases I and II. It is obvious from the percentage increase in Phase II that the two shoulder and thigh straps account for a greater part of the load taken up and that there has been a significant difference in the performance of the harness. It is concluded that any alteration to a restraint system or couch structure should be dynamically investigated to properly evaluate its effect on that system.

It was observed from the motion picture coverage that the restrained human does not take part in the acceleration of the sled until the restraint harness overcomes his inertial load. Initially, the sled is increasing its velocity at a higher rate than the man; however, the difference is dependent upon which portion of the man's anatomy is being measured. A typical data record identifying relative velocity between the sled and subject head is included as Figure 32. As seen from the trace, the man's velocity is equal to sled velocity at peak harness load. Thereafter the man's velocity exceeds the sled velocity, impetus being supplied by the stored energy of the harness converting back into kinetic energy. The subject, having a higher velocity than the sled, moves toward the foot of the couch until contact is made with the thigh support and foot pedestal, causing him to "bottom out". The degree of bottoming depends on the velocity difference between the subject and couch just prior to contact, couch

cushioning, and to a great extent, his own body cushioning. When bottoming occurs, the torso is abruptly stopped by the thigh pedestal but the momentum and c.g. location of the head which is anteriorly eccentric with respect to the supporting vertebral column causes it to rotate up and away from the couch. It is of interest that the highest acceleration reversals caused by bottoming were noted on oscillograph records 18, 24, 28, 36, 38, 60, and 61. In almost all these cases the subject either commented on the severity of the ride or later showed symptoms. Each acceleration trace was integrated to determine maximum subject velocity and this figure was subtracted from maximum sled velocity to obtain their velocity difference, Table 6. This difference increased with increasing sled G, reaching a maximum of approximately 7 ft/sec.

A motion study was undertaken to determine subject head and shoulder displacement relative to each other and the couch during the impulse. A Boscar Model E-1 motion analyser, manufactured by the Benson Lehner Corporation provided a read out of the X and Y co-ordinates to the nearest 0.10 inch. Time base and displacement coverage had been obtained from a Milliken camera mounted over the subject and operating at 400 frames/second. Three reference points were used in the determination of shoulder and head displacement. A point on the couch was selected as zero position. In Phase I, the edge of the mouth accelerometer was taken for head displacement. In Phase II, the inferior surface of the nasal septum was found clearly visible and was used for head reference. The acromio-clavicle junction, being tightly bound down, became a landmark common to both studies. Displacement/time curves were plott for each subject. These are presented as Figures 33-37. Included with each curve are significant symptomatic and clinical findings. It was suspected that upper torso and head symptoms were connected with exceeding a critical hea to shoulder dimension. The curves neither supported nor disapproved this contention. Some symptoms were realized during comparatively small displacements and absent during larger head excursions. Certainly it is recognized that rate of displacement should be considered in conjunction with displacement magnitude as possible factors influencing subject response, although this is not clearly established from the curves. It is quite possible that had higher magnitudes of acceleration and velocity change been introduced (resulting in more disturbing symptoms) a trend would be indicated.

Reviewing Figure 32, it is apparent that there is a time lag between the beginning sled and subject accelerations. Aside from natural frequency considerations, there are other determinations for this time differential. Some of these are:

a. Coupling of the subject to the harness.

b. Subject physique.

c. Elastic deformation of the couch structure and occupant.

d. Amount of slack and slippage at harness attachment points.

This implies that the rate of acceleration onset of the subject depends upon these factors and harness elasticity rather than the input forcing acceleration within the range of pulse configurations applied. The onset rate will be governed in part by the velocity difference between the subject and couch at the time all the slack is taken up and the straps "grab" the occupant. This conclusion was verified by changing the input onset rate by a factor of ten without altering subject onset response (Fig. 38). Changing the wave shape of the input pulse has a direct effect on subject response in terms of altering his acceleration and load distribution pattern. Record pairs having the same velocity change but different wave shapes are offered to substantiate the above statement and are presented as Figs. 39 to 41. Note that peak response occurs at the same time with respect to the beginning of the applied acceleration in each record pair.

The restraint system previously described, was made up of several types of webbing each having a different stress-strain characteristic. Static loads were applied to the straps to determine their stretching properties, (Fig. 42). For identification purposes the letters A,B,C, & D were assigned to the different lengths of harness and percent elongation plotted against load, (Fig. 43). The lower torso V anchor strap, as expected, gave the greatest increase in percentage elongation since it was the only nylon webbing used in the torso restraint harness. The fact that the elongation and therefore the stretching velocity is not uniform means that the subjects torso and limbs will experience different accelerations determined largely by the stretching properties of the web and other materials used to restrict his motion.

X-ray

Although this investigation concerned itself with the measurement of exterior bodily motions in an attempt to explain subject response, an effort was made to obtain a measurement of internal organ displacement. A mobile conventional type X-ray unit available at ACEL for experimentation was used to determine whether a single A-P roentgenogram of sufficient clarity and resolution could be taken at maximum acceleration for comparison with a static exposure. On test firing #61, the unit set to deliver 100 KVP and 200MA at 1/60 second exposure, was synchronized with a programmer to fire at maximum sled acceleration (Fig. 44). As indicated from the oscillograph record (Fig. 45) actuation of the X-ray pulse occurred at peak G.

The A-P roentgenogram when compared to near-simultaneous static film, revealed the following internal motion (Fig. 46): In general there was a whole-body movement headward. Soft tissue moved more than skeletal structure. Unless supported, the more distal the structure from the acceleration source the greater was the movement, as shown by the following measurement: The superior surface of body of L_2 moved 1.0 cm, whereas that of D_8 moved 2.8 cm. Though the transverse colon shadow moved 1.0 cm, the heart and diaphragm were moved upward 6.0 cm. Of interest is the fact that no rotational change in cardiac apex about the base, such as had been postulated as a mechamism for rupture of the aorta, was demonstrated.

Medical

Subjective Comments

It is apparent from an examination of Table 7 that subjective complaints throughout the program related almost exclusively to the upper torso and head area. All participants experienced varying degrees of upper skeletal discomfort, but one subject, (D), continually reported the same symptom with each new exposure. Subject (E) likewise was consistent in experiencing a headache after each firing. Delayed spinal symptoms occurred in several cases and in particular after test #60, although the subject had commented as to the smoothness of the ride. Most subjects noted at various acceleration levels the sensation of an upward shift of their abdominal contents which was not disagreeable nor associated with nausea. No mental confusion or "redout" occurred.

Objective Findings

In general, physical examination of the subjects immediately post-impact revealed no significant change from pre-run examination. Apprehension, quite noticeable at first decreased with increased experience. A moderate facia flush and injection of conjunctivae was noted at the 4G level and was present thereafter. Ophtalmoscopy revealed normal retinae; neuromuscular examination revealed no deficit; skeletal examination revealed no disability nor disturba of locomotion; and inspection of the skin revealed only mild erythema and occasionally petechiae of stress under the restraints. Post-impact examination as well as evaluation of the tape recorded voice showed a clear sensorium in all but one case where dysarthria was noted. The urinalysis was clear except in three cases where microscopic hematuria was found.

Impact induced temporal lobe discharges were demonstrated in six electroencephalograms during Phase I, (Fig. 47). No positive discharges occurred during Phase II. Dysrhythmic pattern over the right postrolandic area following impact reverted to normal on subsequent EEG one week later.

The electrocardiograms of all subjects demonstrated transient sinus bradycardia at impact and for two seconds following, (Fig. 48). A shift of the vector loop was shown in all tracings, (Fig. 49). During Phase I three impact induced atrial premature extrasystoles occurred, and in two cases, premature ventricular beats (3:1) followed impact. Persistent sinus bradycardia (38-42/min.) for 30 minutes followed another impact. Progressive systolic hypertension (172/90) caused temporary rejection of subject A from the program after three firings. During Phase II a tendency to return more rapidly to preimpact levels was noted, but was not of an order of significance. No arrhythmias were demonstrated.

It was clearly evident that the number of complaints diminished at comparable G levels during Phase II. In fact, at the highest levels the subjects commented on the "smoothness of the ride". How much credence can be attributed to these statements is a matter of conjecture since the pulse durat is diminishing to the degree that the subject may no longer be capable of diagnosing the event.

In conclusion, it is important to stress that the input cannot be considered as being truly impulsive loading. The duration which varied from 150 milliseconds to 60 milliseconds was of sufficient order to allow the subject time to react before the pulse was over. It would therefore be without foundation to state that velocity change was the only significant criteria for determining subjective end points. For the durations examined in the program, the pulse shape has a definite physiological effect since it was reflected in the response loading. It is also interesting to note the similarity between this study and the automotive impact program carried out by the Ford Motor Company [(5)]. Instrumented car crashes into barriers yielded input pulse durations and magnitudes very close to those realized in this program. Anthropomorphic dummy seat belt load patterns almost duplicated in time the responses obtained at ACEL. Once again the restraint harness was the determinant for predicting the loading pattern which can be anticipated under crash-impact conditions.

SUMMARY OF RESULTS

Five healthy young men were subjected consecutively to incremental increases of negative acceleration. Each subject, lying in the supine position, was firmly secured through a restraint harness to a rigid couch support. Exposure was discontinued at a sled level of 10.5 G plateau with a velocity change of 17.0 ft./sec. when the subjects displayed increased symptoms of headache, prolonged bradycardia and jolt discomfort. The study was continued after modifications were made to the restraint system, couch configuration and performance of the Horizontal Linear Catapult. The same volunteers were again exposed to increasing acceleration levels until a 14.5 G plateau (as measured on the sled), with a velocity change of 20.6 ft./sec. was reached. At this point in the program NASA decided that the tolerance limits had been sufficiently expanded to satisfy design requirements and the program was discontinued.

Analysis of the oscillographic records revealed that the subject rate of G onset was independent of the sled rate of G onset over the range covered. The natural frequency of the "restraint-man" system was computed to be approximately 4 cycles/sec. The ratio of subject peak head acceleration to peak couch acceleration varied among subjects but averaged 2 to 1. It was dramatically shown that with changes to the couch structure and restraint harness, load distribution into harness attachment points is drastically altered. The motion picture analysis revealed that the subjects' torso and head velocity initially lag behind that of the sled but eventually exceed the sled's velocit until the torso "bottoms out". Displacement of the head relative to that of the shoulder increased with increasing levels of acceleration but did not correlate with subjective complaints. All participants experienced varying degrees of upper skeletal discomfort although the greatest proportion of complaints were expressed by two subjects. Impact-induced temporal lobe discharges were demonstrated in six electroencephalograms. The electrocardiograms of all subjects indicated transient sinus bradycardia at impact and for two seconds following, except in one case where bradycardia was observed for 30 minutes following impact. Three impact induced atrial premature extrasystoles occurred, and in two cases, premature ventricular beats followed impact.

CONCLUSIONS

On the basis of test results it is concluded that:

1. A tolerance limit was not reached. From the symptomatology, there is no way of predicting how close the final level was from a critical point. A discomfort level was experienced at accelerations below 10G during Phase I. With the introduction of restraint and couch modifications in Phase II, the subjects could tolerate a 15G exposure. There is no justification for using these peak levels as ultimate tolerance limits nor can they be taken out of context without relating them to the particular support and restraint used in these series of tests.

2. Any alteration to the restraint system or couch structure may be either favorable or unfavorable and should be investigated to determine its effect on the dynamic characteristics of the system.

3. Closing the "back-thigh" couch angle aided in lessening the man's submarining below his pelvic restraint, but increased the probability of his coccyx making a point contact during rebound.

4. The "V" strap added to the center portion of the lap belt prevented the torso harness from shifting during impact and helped distribute the accelerating force to the pelvic girdle.

5. Three inch wide webbing should be used over shoulder contact areas to insure minimum webbing pressure consistent with comfort. Reduction of the stress per unit area will decrease the physiological effects of negative deceleration.

6. Restricting upper torso displacement by wrap around shoulder straps can cause injury because of head hyper-extension.

7. The NASA Mercury helmet worn throughout Phase II did not interfere with subject motion and did not present any problems during the test series.

8. Varying the sled rate of G onset did not have any effect on subject head and torso response. Changes to the input wave shape had a direct effect in altering the man's acceleration and load distribution pattern.

RECOMMENDATIONS

It is therefore recommended that the following action be taken:

1. A program be undertaken to establish whether physiological limiting effects were determined by initial subject extension or subsequent rebound or perhaps the combination of both these conditions. "Bottoming out" during rebound may be used as the control variable for making this determination since crush up materials are available for placement under the buttocks and thighs for the reduction of rebound loads.

2. Changing the sled rate of G onset over a considerable range did not have any noticeable effect on the subjects dynamic response and it does not appear necessary to specify a "G/sec" limiting value. A more definite statement could not be made since several other variables were introduced into the program at the same time that the onset rate was altered and may have influenced overall system response. A specific investigation should be conducted to ascertain the range over which the input onset rate may be varied without effecting system response and whether it has any meaning at all in this region of impact.

BIBLIOGRAPHY

1. Gaur, O. H.: In Gravitational Stress in Aerospace Medicine. Little Brown & G., Boston, 1961, P. 15

2. Coerman, R. R.: Comparison of Dynamic Characteristics of Dummys, Animals and Man. Impact Acceleration Stress, Publication 977, N.A.S.-N.R.C. Wash. D. C., 1962, P. 173

3. Muller, J. T.: Transients in Mechanical Systems, Bell System Technical Journal, Oct. 1948, P. 657

4. Aldman, B.: Biodynamic Studies on Impact Protection. Acta Physiologica Scandinavica, Vol. 56, Supplementum 192, 1962.

5. Haynes, A. L.: Automotive Impact, Impact Acceleration Stress, Publication 977, N.A.S.-N.R.C., Wash. D.C., 1962

Accelerometer Serial Nos.	Manufacturer	Model Nos.	Range "g"	Natural Frequency (CPS)
1943	Statham	A5A-20-350	±20	350
1379	CEC	4-202	±25	562
1381	"	4-202	±25	582
3101	"	4-202	±50	880
4181	"	4-202	±50	880
5035	"	4-202	±15	545
5036	"	4-202	±15	530
5037	"	4-202	±25	930
5038	"	4-202	±25	725

Galvanometer Serial Nos.	Manufacturer	Model Nos.	Freq. Response (CPS)	Natural Frequency (CPS)
9507	Heiland	M100-350	0-60	100
9671	"	M100-350	0-60	100
39655	"	M100-350	0-60	100
42172	"	M100-120A	0-60	100
42567	"	M100-120A	0-60	100
42665	"	M100-120A	0-60	100
43030	"	M100-120A	0-60	100
9310	"	M1650	0-1000	1650
9337	"	M1650	0-1000	1650

TABLE 1 - Transducer & Galvanometer Type & Natural Freq.

Test Numbers	Transducer Serial Nos.	Galvanometer Serial Nos.	Transducer Location
1 to 10	1943	9671	Horiz. Sled
	5035	9507	Horiz. Couch
	5036	39655	Horiz. Mouth
	#1	43030	Left Shoulder Tensiometer
	#2	42665	Right Shoulder Tensiometer
	#3	42172	Left Thigh Tensiometer
	#4	42567	Right Thigh Tensiometer
	The Following Changes Were Made		
11 to 13	1943	9310	Horiz. Sled
14 to 25	1379	9310	Horiz. Sled
26 to 43	1379	9337	Horiz. Sled
26 to 43	5038	39655	Horiz. Mouth
44 to 56	1381	39655	Horiz. Head
57 to 60	3101	39655	Horiz. Head
61	4181	9337	Horiz. Sled
61	5037	9607	Horiz. Couch

Table 2 - Transducer Location